NASA CR-139181

EXECUTIVE SUMMARY

SPACE SHUTTLE STRUCTURAL INTEGRITY AND ASSESSMENT STUDY

NAS 10-8018

JULY 1974

PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JOHN F. KENNEDY SPACE CENTER
KENNEDY SPACE CENTER, FLORIDA

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FOREWORD

The Space Shuttle Structural Integrity and Assessment Study, Contract NAS10-8018, was conducted by the Lockheed-Georgia Company for the John F. Kennedy Space Center, Kennedy Space Center, Florida. The study was conducted from June 1972 through July 1974 under the technical guidance of the contract technical representative, Mr. R. Sannicandro of DD-SED-4, John F. Kennedy Space Center. The program was managed at the Lockheed-Georgia Company by Mr. W. H. Lewis and the Principal Engineer was Mr. W. M. Pless.

This document presents an executive summary of the study and is submitted in addition to the contract requirements. The complete study documentation consists of

Study Plan	-	LGD/315049, 20 July 1972.
Interim Report	-	"Crack Initiation and Propagation Studies of Space Shuttle Materials", G. Richmond, Lockheed-Georgia Report, 7 December 1972.
Mid-Term Report	-	NASA CR-134452, LG73ER-0082, June 1973.
Mid-Term Report	-	TPS Study, Appendix to NASA CR-134452, LG73ER-0042, June 1973.
Final Report	-	NASA CR-134454, LG74ER-0074, July 1974.
Final Report	-	NASA CR-139180, LG74ER-0075, Appendix to NASA CR-134454, July 1974.
Monthly Status Letters	-	July 1972 through April 1974.

A portion of the study dealing with the NDE requirements for the Solid Rocket Booster was conducted at the Lockheed Propulsion in Redlands, California, under the leadership of Ms. Judith Schliessmann. Design information for the Orbiter vehicle structure and Thermal Protection System (TPS) was obtained from Rockwell International - Space Division in Downey, California, and additional information on the TPS was obtained from the Lockheed Missiles and Space Company in Palo Alto, California.

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ABBREVIATIONS

AE	Acoustic Emission
ET	External Tank
HRSI	High-temperature Reusable Surface Insulation
LRSI	Low-temperature Reusable Surface Insulation
NDE	Nondestructive Evaluation
NDI	Nondestructive Inspection
RCC	Reinforced Carbon-Carbon
SRB	Solid Rocket Booster
TPS	Thermal Protection System

1.0 BACKGROUND INFORMATION

This program is concerned with defining the potential nondestructive evaluation requirements for the entire Space Shuttle vehicle for inspection of the structure during the refurbishment/turnaround period. The objectives of the program are presented in Figure 1. Nondestructive evaluation (NDE) consists of a broad body of technology from which techniques are derived for detecting and characterizing defects in a material without damaging or impairing the material in any way by the NDE process. Airframe structures are susceptible to service-caused defects which are induced by the combination of loads and environments experienced during repetitive missions. Such induced service defects may take the form of fatigue cracks, stress corrosion cracks, corrosion, adhesive disbonds and the like. To assure mission reliability, these defects must be detected and repaired to preclude malfunction or catastrophic failure.

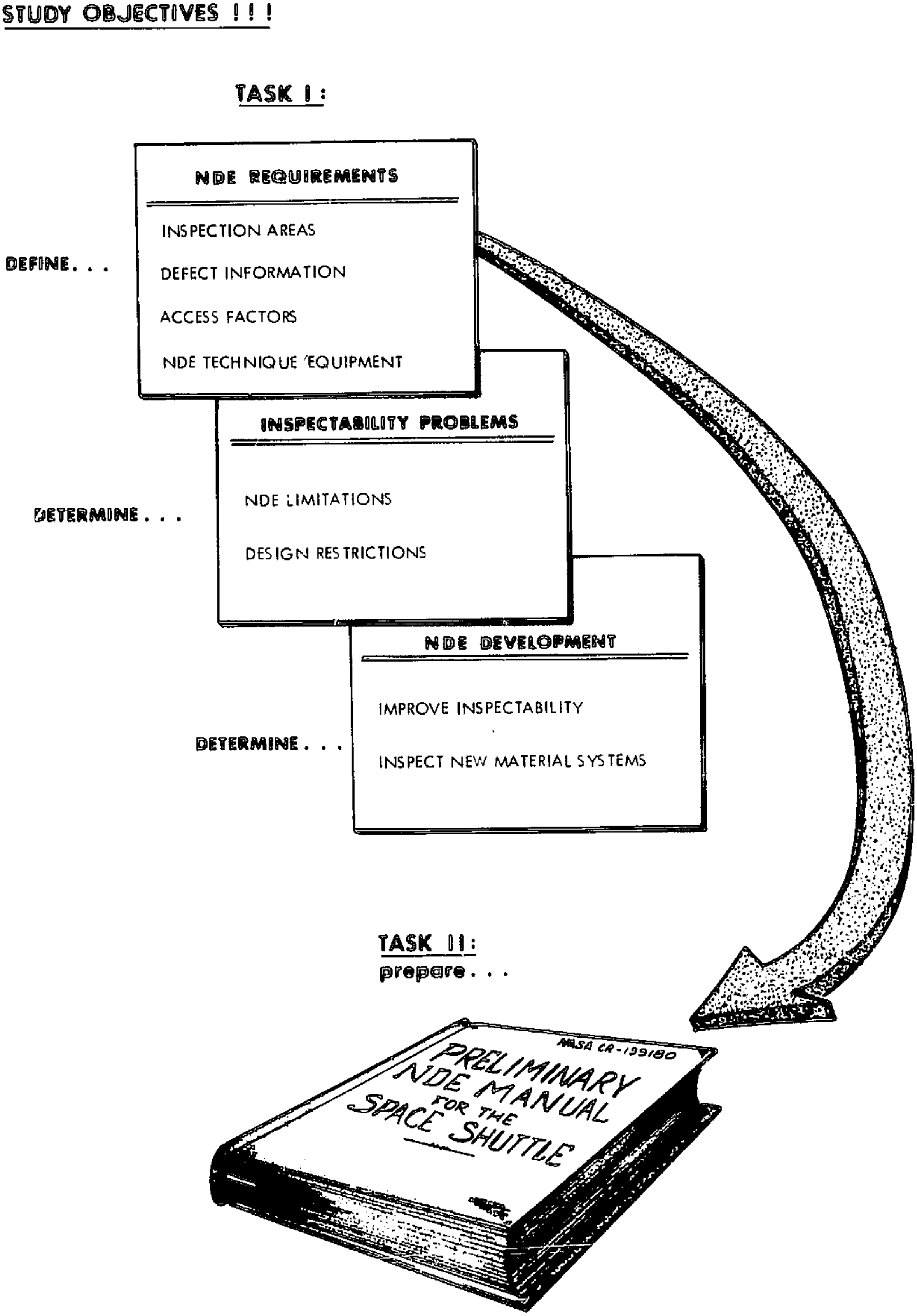


FIGURE 1. STUDY PROGRAM OBJECTIVES FOR CONTRACT NAS 10-8018

For the purposes of this study program, the NDE requirements include a listing of the areas or components of structure which may require refurbishment inspection, information concerning probable defects in the areas, NDE accessibility factors for the areas, and the NDE techniques and equipment which appear most suitable to accomplish the inspection. To develop this information, it was necessary to review numerous Space Shuttle structural design drawings and documents, given in Figure 2, containing design and mission load/environmental data. Drawings and design documents were obtained from the Space Shuttle prime contractor, Rockwell International-Space Division, from NASA/KSC, and from the Lockheed Propulsion Company. Most of the information available during this period was preliminary and lightly detailed so that the resulting NDE requirements themselves are preliminary.

PRIMARY STUDY INFORMATION SOURCES

- DESIGN CONTRACTOR DRAWINGS
- CONTRACT NAS 3-16765, "FRACTURE CONTROL DESIGN METHODS"
- CONTRACT NAS 9-19000:
  - REQUIREMENTS/DEFINITION DOCUMENT STRUCTURES - BOOK 1 JULY 1974
  - SPACE SHUTTLE ORBITER FRACTURE CONTROL PLAN SD73-SH-0082
  - STRUCTURAL LOADS DATA BOOK SD73-SH-0040 JUNE 1973
- (USAF) T.O. 1C-5A-36, TECH. MANUAL, "NONDESTRUCTIVE INSPECTION AND T.O. 33B-1-1, "NONDESTRUCTIVE TEST METHODS"
- NUMEROUS GOVERNMENT - INDUSTRY REPORTS

FIGURE 2. PRIMARY SOURCES OF INFORMATION WHICH PROVIDED THE BASIS FOR THE STRUCTURAL ANALYSIS AND DEVELOPMENT OF NDE REQUIREMENTS

The NDE requirements were compiled into a separate document titled the Preliminary Nondestructive Evaluation Manual for the Space Shuttle which will be described later. This document can serve as a basis from which a full NDE manual and NDE program can be generated for use during the Shuttle refurbishment periods.

It was also an objective of the study to view the inspectability of specific areas in terms of the capabilities of state-of-art NDE coupled with special Shuttle criteria. It was anticipated that some materials may not be inspectable by present NDE techniques and that some areas of structure may not be inspectable because of design or NDE equipment limitations. The outgrowth of such shortcomings naturally would be recommendations for further NDE development or design iterations to provide inspection capability. Recommendations have been made for NDE development for the Thermal Protection System (TPS) and certain areas of structure where limitations presently exist.

Additional recommendations have been made for continuing, extending, and implementing an NDE Program for the Space Shuttle. The greatest benefit from this study may be drawn in the continuing effort.

The remainder of this Executive Summary deals with the specific criteria, guidelines, NDE requirements, and recommendations resulting from the study.

2.0 SUMMARY OF STUDY RESULTS

2.1 Preliminary NDE Manual

The NDE requirements derived under this program were compiled into a separate document identified as the "Preliminary Nondestructive Evaluation Manual for the Space Shuttle" which has the NASA control number NASA CR-139180, and is the Appendix to the study Final Report. This document consists of one (1) section containing

general information and eight (8) sections containing specific requirements for the Space Shuttle vehicles and the thermal protection system (TPS).

General information pertaining to use of the manual, vehicle descriptions, NDE method descriptions, basic NDE procedures and equipment, and safety considerations is contained in Section 1 - General. The defined NDE requirements for the Orbiter's five major subassemblies are contained in Section 2 through Section 6. Section 7 contains the NDE requirements for prelaunch inspection of certain External Tank (ET) components and Section 8 contains the NDE requirements for prelaunch and refurbishment inspection of Solid Rocket Booster (SRB) structure. Section 9 describes the reinforced carbon-carbon (RCC) TPS and the high- and low-temperature reusable surface insulation (HRSI and LRSI) TPS components, their potential failure modes, and candidate NDE methods which require further development.

The procedures contained in the sections on structural inspection provide description and location of the candidate inspection areas, probable defect information, inspection access factors, suggestions for NDE techniques, and descriptive artwork. A sketch of a typical area from one of the preliminary procedures is shown in Figure 3, and is included to give the reader of this Summary a visualization of an NDE procedure from the Appendix document.

MAJOR ASSEMBLY: ORBITER, MID-FUSELAGE, ZONE 4

TYPE INSPECTION: (X) POSTFLIGHT

SUBASSEMBLY: MID-FUS LOWER LONGERON

DRAWING(S): FIG. 1.4.4 of 73MA5769

COMPONENT/AREA DESCRIPTION: WING-TO-FUSELAGE LWR AFT LONGERON TENSION TIE. Located along the lower wing-to-fuselage attachment interface from Fus Sta X_o 1191 to Fus Sta X_o 1307 ($Y_o \pm$ 105) are 72 tension bolts. Two tension bolts are installed in each of 36 riser bays on each side of the fuselage. The mated components include the 2024 aluminum alloy wing lower surface skin panels and the titanium alloy mid-fuselage lower aft longeron which have a zinc chromate primer and Supercorapon 515-700 paint finish. Tension/compression load spectra are transferred through the tension joint during all flight regimes.

DEFECTS: Fatigue cracks may occur around the tension bolt holes in either the wing skin or mid-fuselage longeron.

ACCESS: The holes are to be inspected on both sides of the interface. Enter the mid-fuselage crawl space through the MLG wheel well-fuselage access opening at X_o 1055, and enter the wing through the wing-to-fuselage aft access opening at X_o 1238. For backup inspection, the tension bolt in the suspect hole must be removed.

NDT TECHNIQUES: Primary: Ultrasonic shear wave (para. 1.5.5.3C)
Backup: Eddy current bolt hole (para. 1.5.4.3)

FIGURE 3A. THE ELEMENTS OF A PROCEDURE IN THE PRELIMINARY NDE MANUAL FOR THE SPACE SHUTTLE TYPICALLY CONTAINS COMPONENT NOMENCLATURE AND DESCRIPTION, POTENTIAL DEFECT INFORMATION, ACCESS INFORMATION, AND APPLICABLE NDE TECHNIQUE(S) FOR INSPECTION OF THE PART.

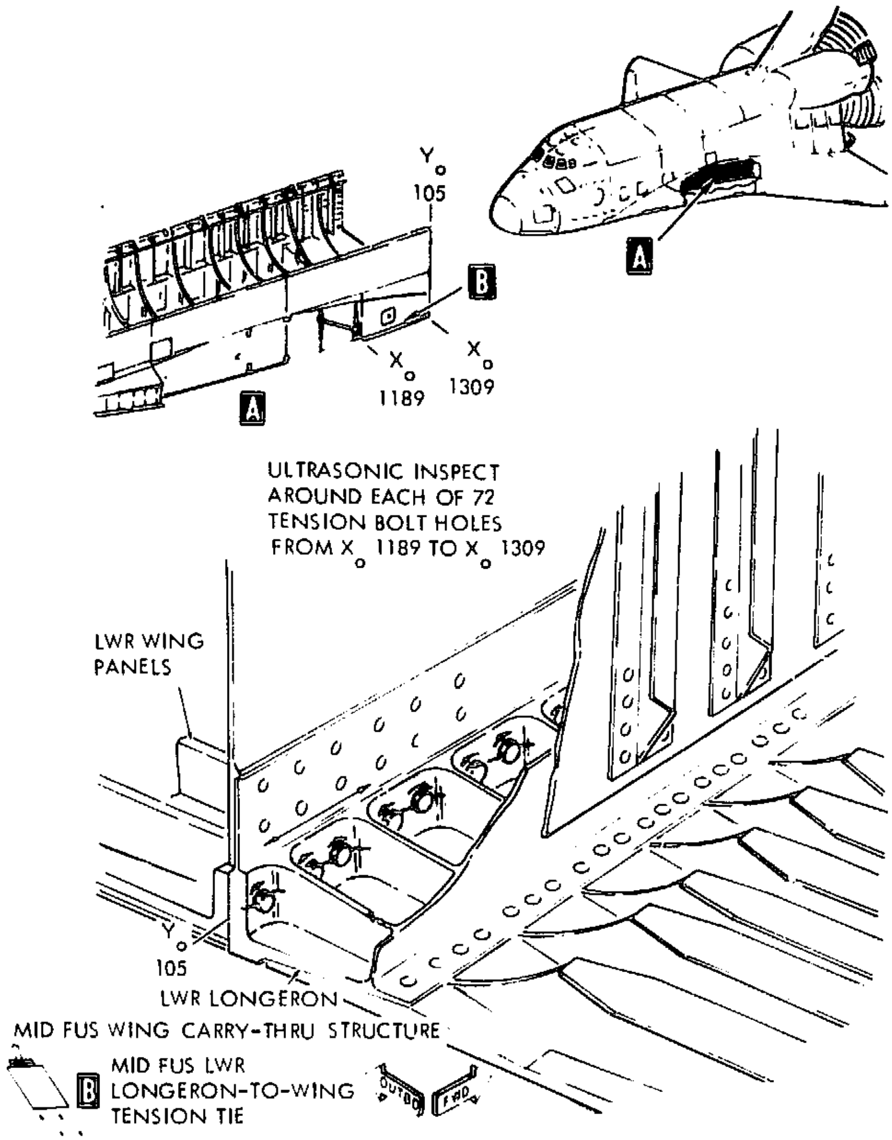
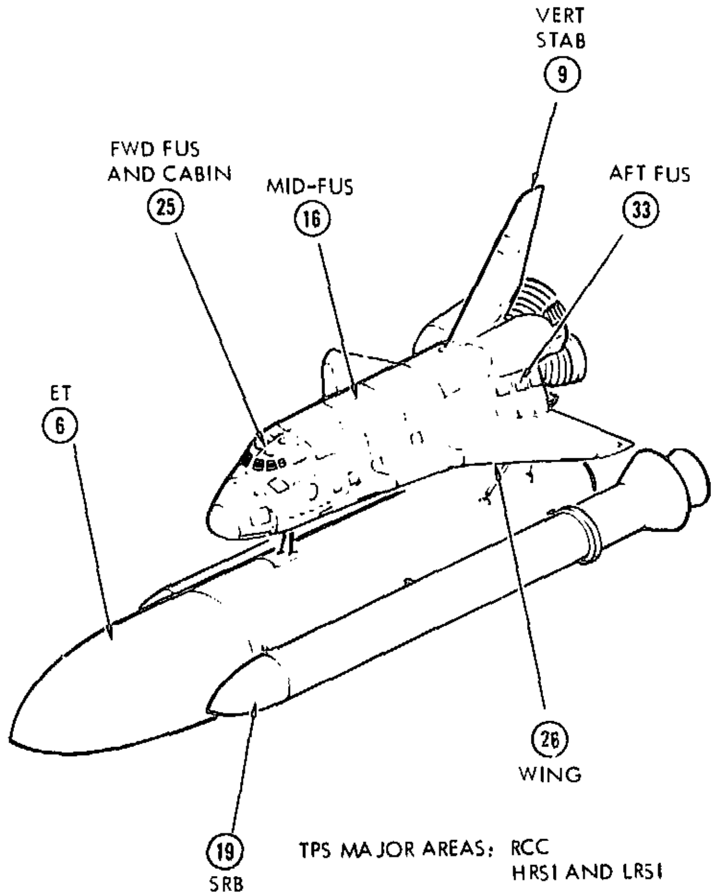


FIGURE 3B. ARTWORK FOR A TYPICAL PROCEDURE IN THE PRELIMINARY NDE MANUAL

Some 134 areas or components of structure are contained in the document and are termed "candidate" inspection areas because a rigorous evaluation of their need and frequency for inspection during refurbishment is yet to be made.

Figure 4 summarizes the number of areas per Shuttle major assembly and subassembly. The NDE procedures contained in the Preliminary Manual were prepared using Shuttle preliminary design information available during the course of this program.



THE CIRCLED NUMBERS ARE THE NUMBER OF INSPECTION AREAS FOR THE SPACE SHUTTLE MAJOR ASSEMBLY OR SUBASSEMBLIES WHICH ARE INCLUDED IN THE PRELIMINARY NDE MANUAL

FIGURE 4. SPACE SHUTTLE STRUCTURAL CANDIDATE INSPECTION AREAS

2.2 Criteria and Guidelines

To arrive at a reasonable and valid set of NDE requirements for Space Shuttle structure inspection, specific criteria and guidelines had to be developed, both for structural and NDE assessment.

The structural criteria used to guide the selection of candidate inspection areas of structure were derived from consideration of Space Shuttle design data and mission loads and from experience on large airframe structures having similar characteristics. Based on the design materials and configurations and anticipated loads and environments, structural areas were selected which may experience some of the induced defects described earlier at some time during the vehicle's operational lifetime. The factors which were considered are detailed in the study Final Report.

In assessing the structure to identify critical areas, Lockheed-Georgia complemented its in-house efforts by making maximum use of the results of Contract NAS3-16765, Fracture Control Design Methods, which also identified some potential fracture-critical elements. The summation of candidate inspection areas is thus a combination of two independent assessments. The NDE criteria were drawn up to guide the selection of NDE techniques that would provide reliable inspection results within the Shuttle refurbishment time constraints. The disciplines from which NDE techniques were selected for structure inspection include visual/optics, fluorescent penetrants, magnetic particle, eddy current, ultrasonics and radiography, which are depicted by the NDI symbol chart in Figure 5.

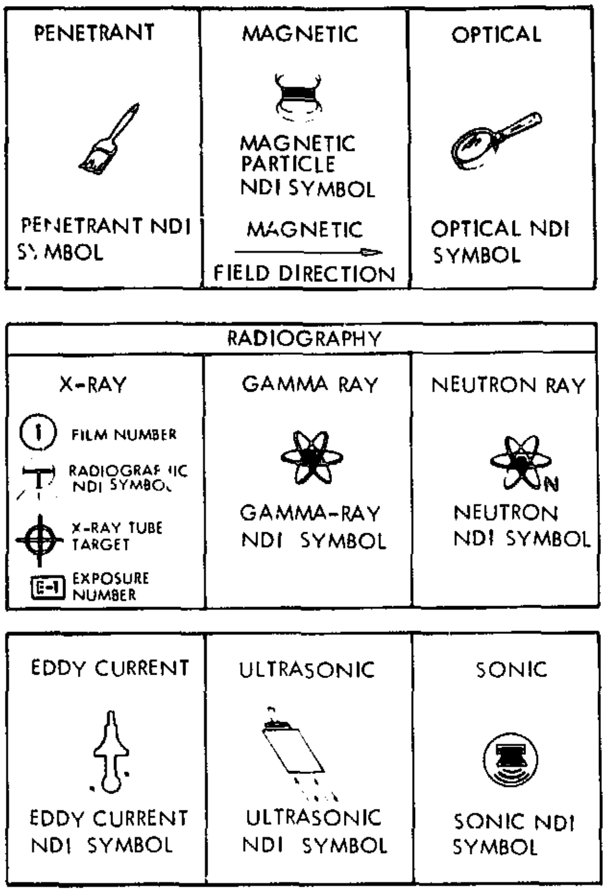


FIGURE 5. NONDESTRUCTIVE INSPECTION METHOD SYMBOLS AS USED IN NDI MANUALS

These are well-known techniques for which inspectors presently are well-trained and certified; inspectors and maintenance managers are generally quite familiar with their capabilities, limitations, and costs; they can be applied readily to Shuttle structural configurations, requiring in most cases a minimum of structure preparation; both sensitivity and reliability data exist for them; they can detect subcritical size cracks in Shuttle safe-life structure; and they require little documentation and data recording facilities. In short, these NDE techniques are the most appropriate ones for refurbishment/turnaround inspection of Space Shuttle vehicles. These criteria and guidelines are discussed in detail in the study Final Report.

NDE techniques and routines applicable to the TPS inspection do not fall generally into the aforementioned category and require development in future or contemporary technology programs. Additionally, NDE of some areas of structure having restricted access can be greatly improved through further technology development. These will be discussed later in Section 2.3.

The refurbishment inspection schedule and inspection frequency will have a major impact on the overall refurbishment schedule. The frequency with which any specific area is to be inspected is dependent upon many factors and must be determined for all inspection-critical areas so that a schedule can be established and integrated into the refurbishment operations. The inspections should be "dove-tailed", fully coordinated with other refurbishment activities, and optimized for maximum manhour per hour expenditure in order to accomplish all inspections in the least elapsed time.

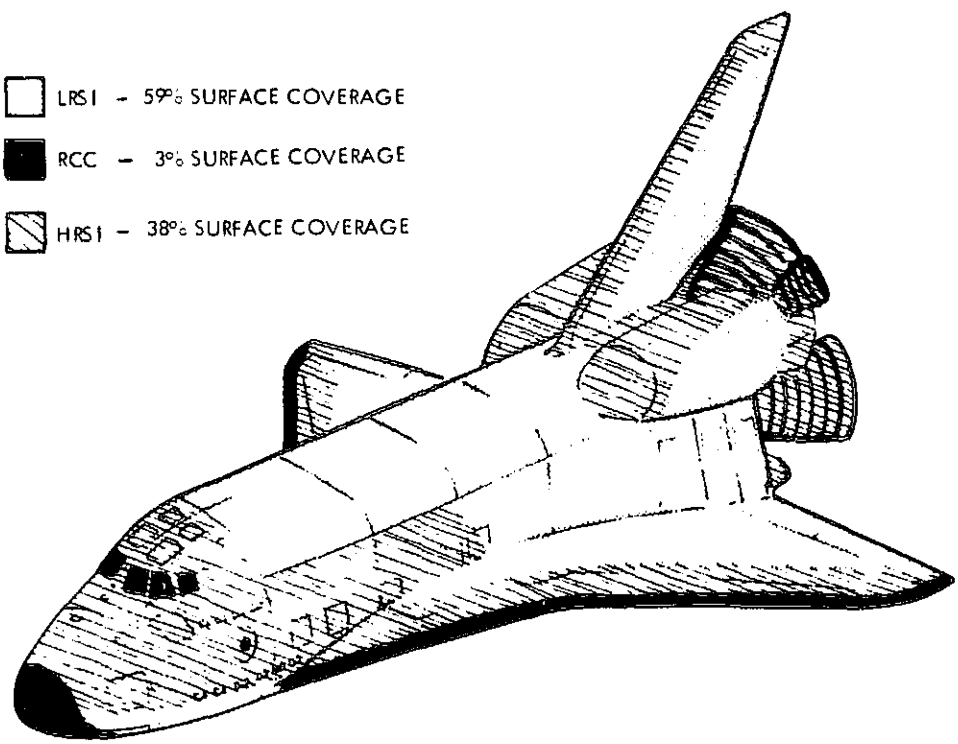
2.3 Recommendations for NDE Development

One objective of the study was to identify areas or components that cannot be inspected adequately because of design factors such as access, material, geometry or configuration, thus posing a possible need for redesign or further NDE technology development. As might be expected for such a large vehicle representing a new system, some areas of structure appear to have this need in one of the two forms. From a gross point of view the needs are brought about because of access restrictions and/or the presence of the TPS which can probably be alleviated in most cases through further NDE development, the use of built-in NDE devices, or the use of alternate NDE approaches - as opposed to consideration for redesign.

From a closer point of view, the inspectability of specific areas in terms of probe clearance, geometry and similar factors could not, in general, be made since detailed design information was not available during the program. The need for redesign is, therefore, largely indeterminate at this standpoint. However, it should be understood that the Space Shuttle vehicles, particularly the Orbiter, appear to be very inspectable structures. Redesign for inspectability, if required, will be very minimal.

Three principal areas were identified to be in need of further development or study: (1) development of primary NDE techniques and inspection routines for the Thermal Protection System, (2) development of an NDE method for detecting honeycomb disbond without removing local TPS, and (3) consideration of built-in NDE devices in access-restricted areas, particularly for crew-module inspection.

The TPS was evaluated early in the study, since it is of major concern because it affects access for structural inspection and requires inspection itself. The application of TPS on the Orbiter is illustrated in Figure 6. The Final Report includes a 10-step



TPS APPLICATIONS

FIGURE 6. TPS MATERIALS IN EITHER THE REINFORCED CARBON-CARBON OR THE COATED SILICA REUSABLE SURFACE INSULATION COVERS ONE-HUNDRED PERCENT OF THE ORBITER'S EXTERIOR SURFACE

plan for developing NDE methods for refurbishment of the Shuttle TPS. Further development is needed because feasible techniques have not been optimized or proven in a maintenance environment, and specific failure modes for the materials have not been strictly identified. Post-flight inspection routines for accomplishing TPS inspection on a large scale should be devised.

This study found that structural areas within the crew module and between the crew module and forward fuselage shell generally have restricted access. To adequately inspect these areas, it is felt that consideration should be given to the use of built-in NDE devices as discussed in the study Final Report. This application should be weighed against other considerations as described.

In this same respect, consideration should be given to the use of acoustic emission (AE) for monitoring certain structural areas. The AE technology that has recently been developed for inflight monitoring of aircraft structure is directly applicable to the Space Shuttle. Specially designed acoustic emission systems can be used to monitor key structural areas and components during all or part of the flight. Such systems hold real promise of greatly reducing cost, manpower, and schedule requirements. An AE system is presently being flight-tested on a C-5A Galaxy transport by the Lockheed-Georgia Company in concert with the Air Force Aeronautical Systems Division.

Further development is outlined in the report for NDE techniques to inspect honeycomb skin panels for disbonds without the need to remove the attached TPS materials. Honeycomb skins are presently planned for use on the rudder, elevons, and aft body flap of the Orbiter. A successful technique can obviously reduce inspection manhours and TPS material costs since TPS removals for this purpose would no longer be necessary. A sketch from one of the preliminary NDE procedures, shown in Figure 7, illustrates the application of honeycomb skin panels to the aft body flap and its inspection problems with the TPS.

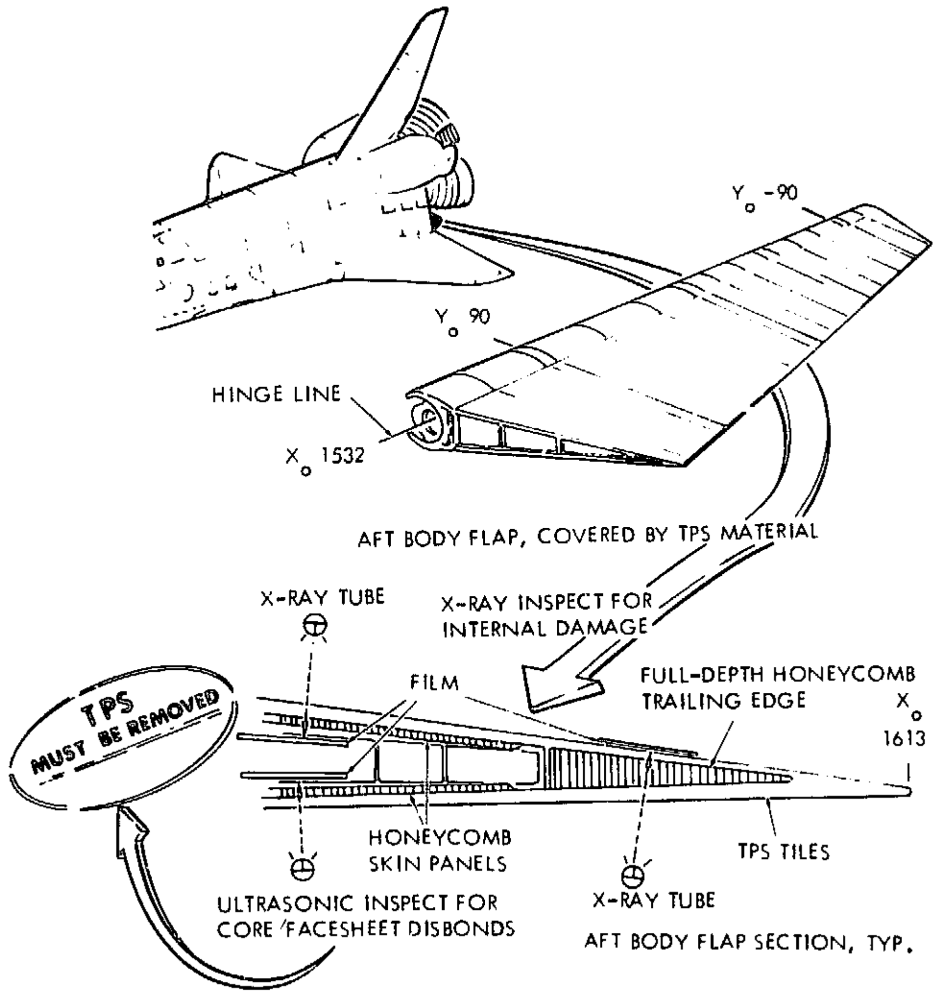


FIGURE 7. HONEYCOMB SKIN PANELS ON THE AFT BODY FLAP, ELEVONS, AND RUDDER NEEDS DEVELOPMENT OF NEW NDE TECHNIQUE TO DETECT DISBONDS WITHOUT REMOVAL OF TPS

3.0 NDE PROGRAM RECOMMENDATIONS

One of the most important features of this study program was to review the NDE plans for the Space Shuttle and to formulate recommendations regarding the refurbishment inspection requirements. The recommendations presented in this study Final Report are outlined in Figure 8 and summarized in the following paragraphs.

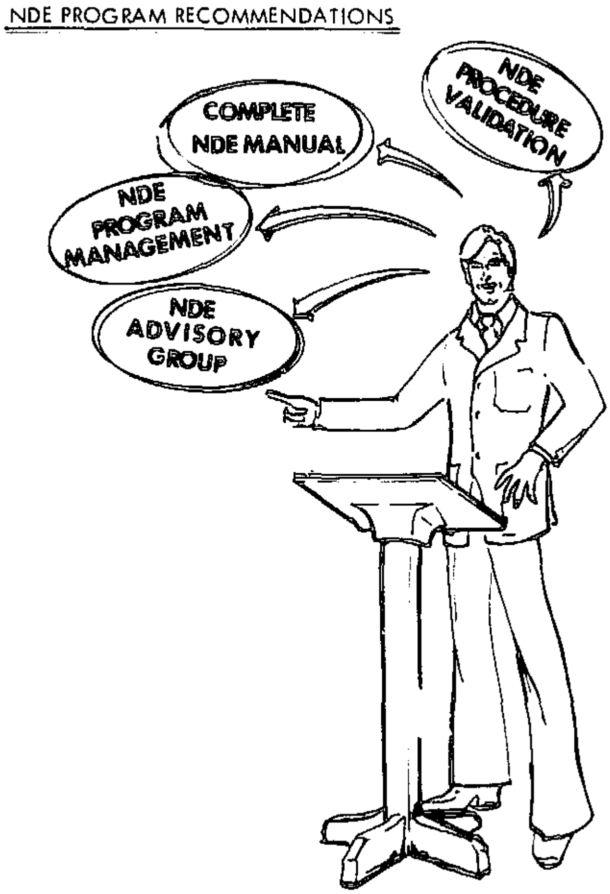


FIGURE 8. RECOMMENDATIONS FOR OVERALL NDE PROGRAM FOR THE SPACE SHUTTLE RESULTING FROM STUDY

3.1 NDE Program Management

It is strongly recommended that a single point of responsibility be established to provide NDE guidance and direction throughout the entire Space Shuttle Program. A single, identified, NDE Program Management source would provide many long-range benefits, including: effective coordination of all contractors to require the proper design emphasis on inspectability, appraisal of NDE technology requirements and related R & D

needs, guidance to all contractors in the preparation of procedures for and use of the NDE Manual, and planning and scheduling of NDE operation during refurbishment.

3.2 Space Shuttle NDE Manual

It is recommended that NASA develop an NDE Manual containing the detailed NDE procedures to be accomplished during refurbishment inspection of Space Shuttle hardware. The Manual should be developed for training purposes and to provide detailed specific instructions to those performing NDE during refurbishment/turnaround. It is imperative that these instructions be mandatory and explicitly followed to ensure that all inspections are repeatable, reliable, and conducted to the proper sensitivity requirements.

The actual NDE procedures should be developed by the prime and major subcontractors in accordance with a Space Shuttle NDE Manual Preparation Guide. Overall coordination and management of the final document should be provided by a single source to produce an effective and consistent NDE Manual. The procedures from the various contractors and sub-contractors must be integrated into a unified, consistent, final document usable by refurbishment inspection personnel.

It is important that each contractor who provides NDE data for the final Manual develop efficient management tools to coordinate information flow between the many technical groups who provide inputs. The design, stress, fracture mechanics, structural test, manuals illustrators/writers and validation/verification disciplines have to interface in a manner to produce NDE procedures that are accurate, effective, and workable as well as be responsive to design changes and serialization. This requires an intricate management control system that is not readily apparent to those who have not undergone a complete NDE Program/Manual experience. An interdisciplinary approach to manual development, controlled by an NDE coordinator or manager, is illustrated in Figure 9.

NDE PROCEDURE AND MANUAL DEVELOPMENT MANAGEMENT

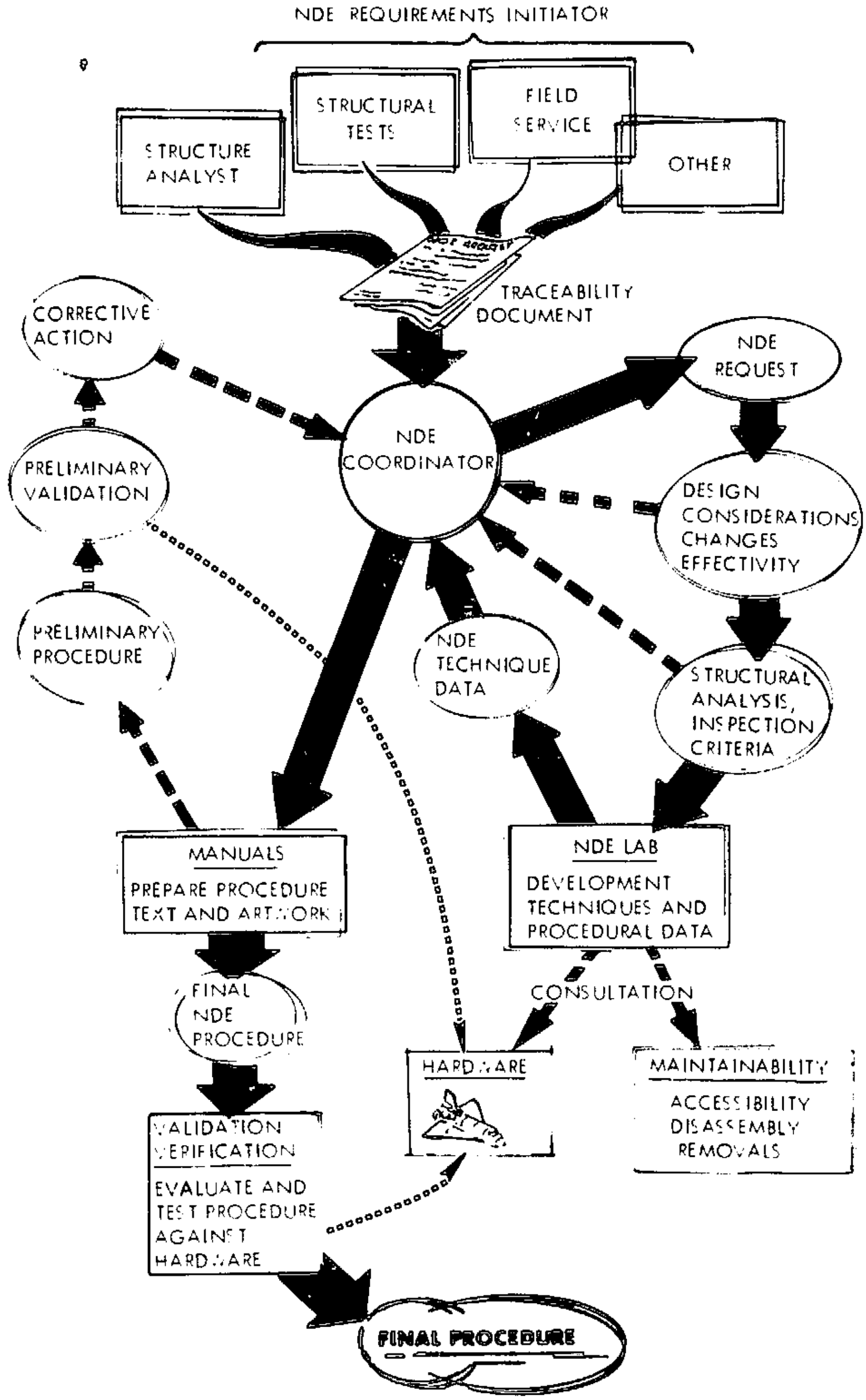


FIGURE 9. DEVELOPMENT OF NDE PROCEDURES FOR THE SPACE SHUTTLE SHOULD HAVE A VALID POINT OF ORIGIN, INTERFACE WITH PROPER ENGINEERING DISCIPLINES AND PROVED ON ACTUAL HARDWARE. PROCEDURE DEVELOPMENT IS MANAGED AND COORDINATED BY AN NDE COORDINATOR AND HAS COMPLETE TRACEABILITY ASPECTS.

3.3 Validation and Verification of NDE Procedures

The design contractor should assure the validity of all essential details of the NDE procedures by testing them against the structural areas on actual Space Shuttle hardware. In order to ensure that the NDE procedures are indeed workable and efficient, NASA should additionally have the procedures verified. The verification should be accomplished by the organization that will be performing the NDE work during refurbishment. If an NDE contractor will be utilized they should be selected at the earliest possible time to allow maximum cognizance and input by the using organization, the NDE contractor.

Validation and verification activities are performed on a given NDE procedure before it is approved for inclusion in the manual. When a procedure must be corrected to satisfy validation or verified requirements, the procedure may have to be re-validated partially or completely, and then reverified by NASA and the NDE contractor if appropriate.

NASA should consider where and how often procedures should be verified. It is likely that verification at both final assembly and flight test locations may be required in order to efficiently utilize hardware of the correct configuration. Verification of groups of procedures sufficient to provide one to two weeks working time has proved reasonable and efficient and should be considered.

3.4 NDE Advisory Group

It is recommended that NASA establish a Space Shuttle NDE Advisory Group to enhance communications between affected organizations and ensure the best possible resolution of NDE-related problems. The Advisory Group should be composed of technical representatives from the various NASA centers and the major Shuttle contractors and should have scheduled meetings chaired by the source responsible for the Shuttle NDE

Program. The Group would provide the ideal forum for:

- Review of recommendations regarding new NDE technology development,
- Resolution of design interfaces between contractors influencing NDE requirements,
- Overall scheduling of NDE Manual development,
- Continued NDE support from major contr s during the .rvice life of the Shuttle,
- Publication of periodic status reviews of the Shuttle NDE Program.